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THEORETICAL PRINCIPLES OF AERATION

Paul D. Haney

Environmental Health Center
Cincinnati, Ohio

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THEORETICAL PRINCIPLES

OF

AERATION

by

PAUL D. HANEY

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THEORETICAL PRINCIPLES OF AERATION

Definitions and Introductory Discussion

Aeration of water may be considered as an example of a useful class of industrial processes involving mass transfer between phases.

In water works practice one phase is always water and the other is a gas, usually air, but occasionally a mixture of air and other gases. As applied to water treatment the term "aeration" may be defined as the process whereby the water is brought into intimate contact with a gas, usually air, for the purpose of transferring highly volatile substances to or from the water. These substances may include oxygen (O_2), carbon dioxide (CO_2), nitrogen (N_2), hydrogen sulfide (H_2S), methane (CH_4), and various, unidentified, volatile organic compounds responsible for taste and odor. Oxygen, nitrogen, and carbon dioxide are universally present in air and all the substances previously named are encountered in various natural waters. Carbon dioxide may be introduced by treatment methods as for example, the CO_2 formed by certain coagulation reactions. Addition of chlorine to water might be considered to fall within the scope of this definition. However, chlorination represents a special case of gas transfer and while certain of the principles of aeration apply, the addition of chlorine to water is accomplished by highly specialized equipment. Consequently the chlorination process is not considered pertinent to this discussion. Recarbonation (addition of CO_2) of a softened water is another treatment method not ordinarily classed as an aeration process; however, it is fundamentally similar and is often accomplished with equipment like that used in certain types of aerators.

Aeration finds its greatest application in the field of the absorption and release of the true gases; e.g., oxygen and carbon dioxide.

Aeration Types: On the basis of present day practice structures or equipment for aeration may be classified into two general types:

(a) Waterfall aerators. (Examples: spray nozzles, cascades, multiple trays.)

(b) Injection aerators. (Example: bubbles of compressed air passed through the water.)

The waterfall type accomplishes aeration by causing the water to break into drops or thin layers thereby increasing the exposed area to volume ratio. The injection type (also called "bubble" or "diffusion" aerator) accomplishes the same thing through the discharge of bubbles of air into the water through special injection devices such as perforated pipes or porous plates. Inasmuch as "diffusion" is a well recognized natural phenomenon applicable to both kinds of aerators and to various other processes of mass transfer the adjectives "injection" or "bubble" are preferable as descriptive terms for this type of aeration.

Aeration Objectives: The basic purpose of aeration is the improvement directly or indirectly of the chemical and physical characteristics of water for public and industrial supply (1). Improvement by aeration may be obtained through the physical removal or addition of substances as follows:

Removal

(a) Taste and odor producing substances such as H_2S and to a limited extent certain volatile organic compounds responsible for taste and odor.

(b) Corrosive substances such as CO_2, H_2S and in many industrial water supplies, O_2 (de-aeration process).

(c) Substances which consume or interfere with chemicals used in subsequent treatment. (CO_2 reduction before lime softening; H_2S reduction before chlorination.)

(d) Methane which might create an explosion hazard if left in the water.

Addition

(a) Oxygen for improvement of taste and odor and for subsequent oxidation of iron, manganese, H_2S, and to a limited extent, organic matter.

(b) Carbon dioxide for recarbonation of softened waters and for assistance in H_2S removal.

Reaeration: As applied to water in streams, lakes, etc., the process of dissolved oxygen absorption generally termed "reaeration" or "reoxygenation" is fundamentally the same as the aeration process used at a water treatment plant and may be looked upon as a special case of the broad subject of gas absorption. In polluted water the mechanism is complicated by the oxygen demand of the pollutants, ordinarily not an important factor in water works aeration. The phenomenon of reaeration of natural bodies of water has been widely studied because of its vast importance in connection with water pollution problems (2) (3) (4) and will not be given specific consideration in this discussion.

Scope of This Discussion: This discussion of the theoretical principles of aeration will be limited largely to the addition and removal of oxygen and carbon dioxide. Quantitative discussion of the theory of removal by aeration of taste and odor producing substances is

limited by uncertainties as to the nature and behavior of the minute amounts of the substances causing odor and taste. Recent work reported by Middleton, Braus, and Ruchhoft (5) may lead, after further research, to a better understanding of the whole problem of taste and odor in water.

Investigations of the Aeration Process

The mechanism of the transfer of gases between gas and liquid phases has been studied by Adeney and Becker (6), Whipple, Fair, and Whipple (7), Roe (8), Lewis and Whitman (9), Baylis (10), Nordell (11), Powell (12), and numerous other investigators representing various fields of interest. References (12) through (21) list a few of the other contributors.

A good bibliography containing references to much of the important work done prior to about 1930 has been prepared by Baylis (10). Probably of greatest interest to the water works profession is the Baylis (10) discussion of aeration for it is presented from a water treatment standpoint. Many other investigators have presented excellent discussions and experimental data and through their efforts have contributed much toward a better comprehension of the aeration process. However, their reports have been concerned to a great extent with applications to the process industries or sewage treatment (18) (21). The greatest amount of study has been devoted to the injection or bubble type process of gas transfer because this method is used in the process industries and also in sewage treatment.

The chemical industry generally terms the addition of gas to a liquid as "absorption" and frequently speaks of the removal of gas from a liquid as "desorption" or "stripping". Theoretically the latter terms may be looked upon as "negative absorption".

The theory of absorption of gases, as for example, the addition of oxygen to water, has been quite well developed (22) and widely applied. These theoretical principles for gas absorption are assumed to apply as well to the release of gases from water, since as previously mentioned, the release of a gas from water may be assumed to be "negative absorption". This assumption appears to be valid (9) (10) (22).

Fundamental Concepts

Before the theory of the aeration process can be developed it is necessary to consider several important physio-chemical principles, including equilibrium, gas solubility, diffusion, and the properties of a gas-liquid surface (interface).

Equilibrium: As applied to dissolved gases "equilibrium" means no further change in concentration of the dissolved gas with the passage of time. Equilibrium is a steady or static state insofar as the concentration of dissolved gas is concerned. Considering aeration from the standpoint of gas transfer, the term implies promotion of equilibrium between the gaseous constituents of water and those of the atmosphere (44). Water exposed to air tends to reach equilibrium with the air; the function of aeration is to speed up this natural process. True equilibrium is mainly of theoretical interest as it is

frequently impractical and generally unnecessary to achieve it. Nevertheless, equilibrium or saturation concentration is an important concept because it is the difference between the equilibrium concentration (saturation value) of a gas and its actual concentration that is the driving force available to cause interchange of gas between air and water. If a water is undersaturated with oxygen when in contact with air, oxygen will go into solution slowly and equilibrium will gradually be approached from the direction of undersaturation toward saturation. If on the other hand the water contains more oxygen or, as is more frequently the case, more carbon dioxide than corresponds to saturation when exposed to air, oxygen or CO_2 will be released and equilibrium will be approached this time from the direction of supersaturation. Agitation of the water, i.e. aeration, by stirring, by breaking the water into drops or thin layers or by blowing bubbles of air through it will speed up this process. The best that aeration can accomplish is the speed-up of a process which goes on naturally. As previously stated, as a practical matter, it may not be possible to establish exact equilibrium with any reasonable amount of aeration but it can be approached in many instances.

Solubility of Gases in Water: Like solids each gas has its own solubility characteristics. Factors governing gas solubility in water are temperature, pressure, dissolved solids in the water and chemical nature of the gas. Unlike many solids, gases exhibit decreasing solubility with increasing temperature. For pressures up to about one atmosphere and for gases which do not react chemically to any great

extent with water the mass of the gas which will dissolve in water at a given temperature is directly proportional to the partial pressure of the gas in contact with the water (23). This relationship is called Henry's Law.

Henry's Law may be expressed mathematically as follows:

$$S = HP \quad \begin{pmatrix}\text{equilibrium conditions and} \\ \text{constant temperature}\end{pmatrix} \quad \text{(Eq. 1)}$$

where

S = concentration of gas in the water, at equilibrium.

P = <u>partial</u> pressure of the particular gas in the air or other gas in contact with the liquid.

H* = Henry's Law solubility coefficient.

Henry's Law applies to the gases most frequently considered in connection with the aeration of water, i.e. oxygen, nitrogen, methane, and carbon dioxide. The latter does react with water as follows:

$$H_2O + CO_2 \rightleftharpoons H_2CO_3$$

and the carbonic acid (H_2CO_3) formed ionizes as follows:

$$H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$$

$$HCO_3^- \rightleftharpoons H^+ + CO_3^{--}$$

However, at ordinary water temperatures and at the concentrations of CO_2 encountered in natural waters less than 1% of the dissolved gas will be in the form of H_2CO_3 (9) (33). Furthermore, the carbonic acid (H_2CO_3)

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*If S is in parts per million and P in atmospheres, the dimensions of H will be ppm/atmosphere.

ionization constants are extremely low. Hydrogen sulfide is encountered in certain ground water supplies. This gas also undergoes chemical reactions in water. The dissolved H_2S will ionize to a slight extent as follows:

$$H_2S \rightleftharpoons H^+ + HS^-$$
$$HS^- \rightleftharpoons H^+ + S^{--}$$

H_2S will also react with alkaline constituents in natural waters so that much of it may be present as sulfide ion, S^{--}, rather than as H_2S (11) (25).

Henry's Law does not apply closely to the more soluble gases such as chlorine and ammonia which readily form compounds with water but these gases are not of great significance as far as aeration is concerned.

Dissolved solids such as salt lower the solubility of gases in water. For example oxygen dissolved in water in equilibrium with air at 1 atmosphere of pressure is lower in sea water than in fresh water (24).

Temperature	PPM Chloride in Water	Equilibrium Concentration of Dissolved Oxygen - PPM
20°C	0	9.17
20°C	20,000 (sea water)	7.42

However this lowering of gas solubility of dissolved solids is a minor factor insofar as most water supplies are concerned. Temperature and pressure are the major factors governing gas solubility in most natural waters. Pressure effects can be estimated by Henry's Law as already indicated but there is no simple relationship between temperature and solubility. However, adequate tables of data showing gas solubility at various temperatures are available (11) (24) (26).

From the discussion given it should be evident that it is not correct to speak of the solubility of a gas in water without specifying temperature and pressure. However, as a practical matter, the partial pressures of oxygen and carbon dioxide in air are frequently assumed to be constant or reasonably so at about 21% by volume or 0.21 atmosphere and 0.035% by volume or 0.00035 atmosphere respectively (11). Therefore pure water at 20°C (68°F) exposed to air (21% oxygen) at a pressure of one atmosphere and in equilibrium with it will contain 9.17 parts per million of dissolved oxygen and 0.5 part per million of dissolved carbon dioxide (0.035% CO_2 in air). These are the saturation values of the two gases at the specified temperature and the indicated partial pressures. The saturation value for a gas is its equilibrium concentration for the specified conditions. The saturation values for CO_2 and O_2 (20°C) are usually assumed to be those previously given. However, it must be remembered always that these and other saturation values at other temperatures can differ appreciably from published values if the partial pressures of the gases change as for example as a result of lowered oxygen partial pressure by increased altitude above sea level or change in CO_2 content from about 0.035% in country air to 0.06% in an industrial area (11). Most published data are in terms of gas solubility in distilled water. Dissolved salts may be present in some natural waters to an extent sufficient to require a significant correction (24).

Diffusion: A few large crystals of copper sulfate placed in a glass of water will sink to the bottom and slowly go into solution. If the water is not mixed by stirring or by thermal currents the layer of blue

colored copper sulfate solution will remain in the bottom of the glass for some time. However, if left long enough and without any apparent mixing whatsoever the color will become uniform indicating uniform concentration of copper ion throughout the water. This slow mixing of the copper sulfate with all the water in the glass is achieved as a result of the process of diffusion. Evidently diffusion tends to produce a stable state of uniform concentration. Water flows through a pipe from a point of high head to one of low head at a rate proportional to the square root of the head difference. Heat flows by conduction from a point of high temperature to one of low temperature at a rate proportional to the temperature difference. In the case of water flow the driving force is a function of the difference in head; for the heat flow example, the "drive" is furnished by the temperature difference. For diffusion the "drive" is concentration (e.g., ppm) difference of the substance being diffused. In the cases of water and heat, head and temperature change per unit of length are termed hydraulic and temperature gradients, respectively. For diffusion this same measure is the "concentration gradient."

The rate of molecular diffusion of a dissolved gas in a liquid is dependent on the characteristics of the gas and liquid, the temperature, the concentration gradient and the cross section area through which diffusion occurs. These various factors may be combined into a differential equation of diffusion which is often termed Fick's Law (27).

$$\frac{dm}{dt} = -DS\frac{dc}{dx} \qquad \text{(Eq. 2)}$$

where:

$\frac{dm}{dt}$ = time rate of mass transfer by diffusion

S = cross section area through which diffusion occurs

$\frac{dc}{dx}$ = concentration gradient (mass per unit volume per unit of length) in the direction perpendicular to the cross section area.

D = a constant, characteristic of the solute and solvent at a given temperature, called the <u>diffusion coefficient</u>.

(The dimensions of D are $\frac{L^2}{T}$, e.g. $\frac{cm^2}{hr}$)

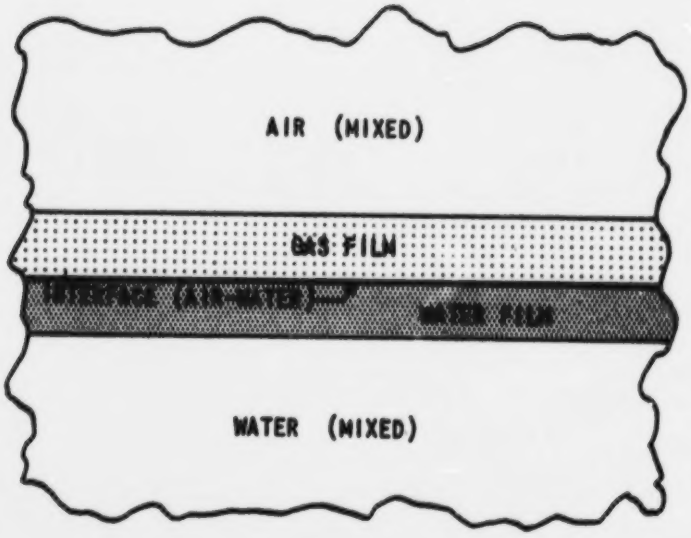
This equation is fundamentally the same as that used to describe the performance of all types of aerators. This is true because it is molecular diffusion through films at the water surface that controls aerator performance to a great extent. Application of a diffusion equation to reaeration has been discussed by Velz (28).

<u>Surface Properties</u>: It is evident from what has been presented previously that "equilibrium or saturation represents the ultimate state" (9) which water exposed to air or other gas tries to assume and that this is a characteristic of primary importance to the aeration process. The second important characteristic of the aeration process is the rate at which the water approaches equilibrium and consideration of this rate is one of the principal objects of this discussion. Equilibrium and rate of approach to it are not independent of one another for under comparable conditions the "driving force" and hence the rate of approach is greater the further the system is from equilibrium.

One of the important factors affecting this rate of approach to equilibrium or saturation apparently is the formation of"films" at the water-air surface which offer resistance to gas transfer. The surface film effect may be roughly visualized by analogy to a thin layer of oil floating on the surface of a body of water which is subjected to agitation. If the oil spreads uniformly it will form an effective seal even though there is considerable turbulence in the water body. (See Figure 1 which shows, diagrammatically, gas and water films.)

An air-water surface or interface presents some striking properties with respect to the properties of the main body of water or air. There is evidence (29) that when a water-air (or other gas) surface is formed molecules at the interface become oriented into a definite pattern thus losing the free and aimless movement characteristic of the molecules of the main body of the gas and liquid. See Figure 1. These "films" of oriented molecules constitute an important barrier to the transfer of gas to or from the water. Evidence has been found which indicates that the extent of molecular orientation at the surface is sufficient to produce a noticeable effect on the characteristics of the surface region (29). The orientation increases with increasing dissymmetry of the molecules involved and decreases with increasing temperature (29). The oriented molecules probably do not mix with the rest of the gas or water even though the water and gas are in a state of turbulence (10).

Ippen and others (30) in describing experiments on bubble aeration refer to work conducted by Zdonik and state that the fact that a film of water is carried along with the bubble in its ascent (through water) was



GAS AND LIQUID FILMS

FIGURE 1

rather uniquely determined by allowing the bubble to penetrate a mineral oil layer at the top of the water column. Water could be seen draining off the bubble and attempts were made to measure the amount of water in order to calculate the liquid film thickness.

Bartholomew (17) in discussing oxygen transfer through air bubbles or other air-liquid interfaces states that the diffusion resistance was found to be located in the liquid phase and that its magnitude depends upon the presence of adsorbed surface-active material at the interface.

It seems probable that substances such as soaps, detergents, organic acids and many others when present in water in minute amounts, would be capable of causing considerable resistance to gas transfer through their influence on the characteristics of the air-water interface. Kehr (31) presented data showing the adverse effects of a variety of substances (oils, soaps, organic acids, raw and treated sewage) on the rate of transfer of atmospheric oxygen to water. In Kehr's experiments 6 p.p.m. of soap in water in an aeration test channel reduced the reaeration rate about 50%.

There is little doubt that film forming substances are present in all natural waters and in air. Passage of gas through these gas and liquid films must be by the process of gaseous and liquid diffusion and this is a very slow process. Turbulence apparently decreases film resistance as does increased temperature. A high velocity gradient across the interface has a similar effect.

Film "thickness", a fictitious length (22), is a useful means of visualizing resistance to gas transfer and can be calculated from

absorption data. The thickness of a quiescent water film has been estimated to be of the order of 0.2 centimeter (0.08 inch) (9) (10). On the other hand a falling drop of water which has a high velocity gradient across the interface has been estimated to have a water film "thickness" of the order of 0.0003 cm. (0.0001 inch) (10) (33). The relative film "thickness" or "aeration resistance" values are more important than the absolute values. Thus the film "thickness" or resistance ratio is about 700:1 for water at rest compared to a falling drop.

The film "thickness" is believed to increase with exposure time (10).

One set of experiments by Adeney and Becker (7) quoted by Lewis and Whitman (22) gave data which indicated a water film "thickness" for rising bubbles of 0.001 cm. (0.0004 inch) about four times that of falling drops (comparable calculation method) (9) (10). Computations based on Ippen's (30) recent experiments with small air bubbles give lower film "thickness" or resistance values. (See Table 2).

Surface Tension: Another surface property of considerable interest and importance in aeration processes is that of surface tension. Fluid surfaces exhibit certain features of a stretched elastic membrane. When air and water are in contact, at the water surface the inequalities of molecular attraction (cohesion) together with other forces change the shape of the surface to produce a minimum potential energy value (27). For example on oil drop suspended and at rest in a liquid of the same density as the oil assumes a spherical shape as a result of the force of surface tension. On the other hand a drop of water hanging from a faucet

or the end of a pipette takes on a pear shape because it is acted upon by the forces of both surface tension and gravity. Surface tension plays a part in drop formation and is a very important factor in the formation of air bubbles in water.

Rate of Gas Transfer in an Aerator

Adeney (6) as a result of studies of bubble aeration proposed the following equation to describe the solution of oxygen and nitrogen in water from fairly large bubbles:

$$w = w_1 - (w_1 - w_o)\, e^{-f \frac{a}{v} t} \qquad \text{(Eq. 3)}$$

where

w = concentration in the water at the end of "t" minutes

w_1 = saturation concentration at the given temperature and pressure

w_o = initial concentration when $t = o$

f = coefficient of escape of gas from the water per unit of area (varies with temperature)

v = volume of the water

a = area of surface exposed

e = base of natural logarithms = 2.718+

The Adeney equation may also be written:

$$\log_{10} \frac{w_1 - w}{w_1 - w_o} = -\left(\frac{f}{2.303}\right)\left(\frac{a}{v}\right) t \qquad \text{(Eq. 4)}$$

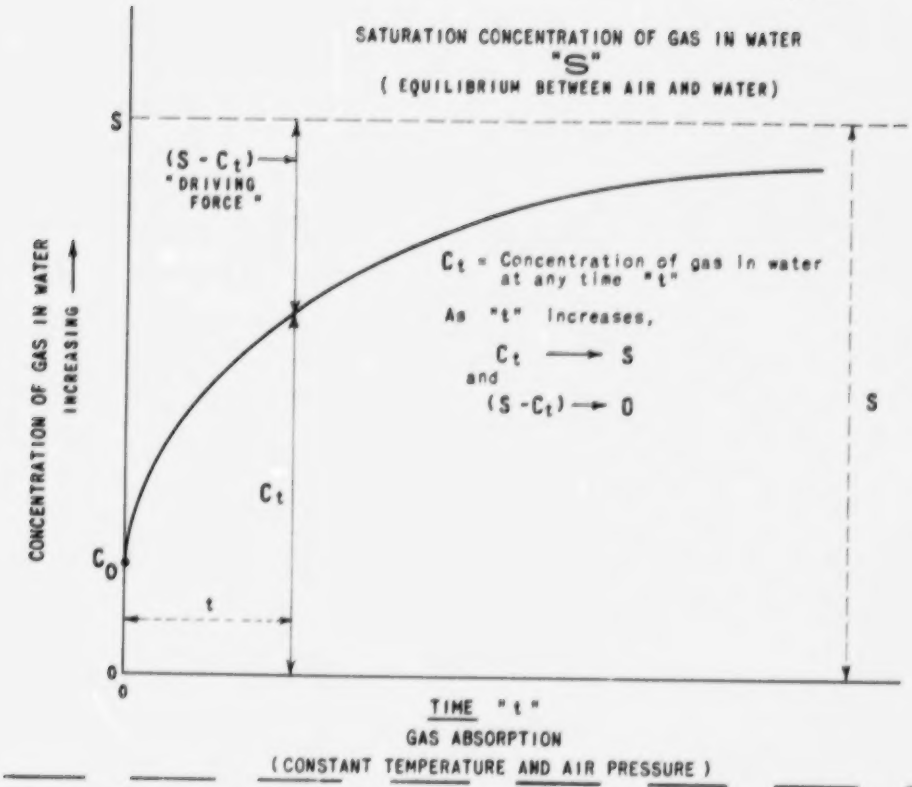
One of the best of the analyses of the gas absorption process is that provided by Lewis and Whitman (9) (32). Methods of applying the original Whitman two film theory have been gradually developed and refined in the 30 year period since the theory was proposed and, despite the fact that the theory has never been completely checked experimentally (22), it is highly useful in the design of gas absorption or release devices.

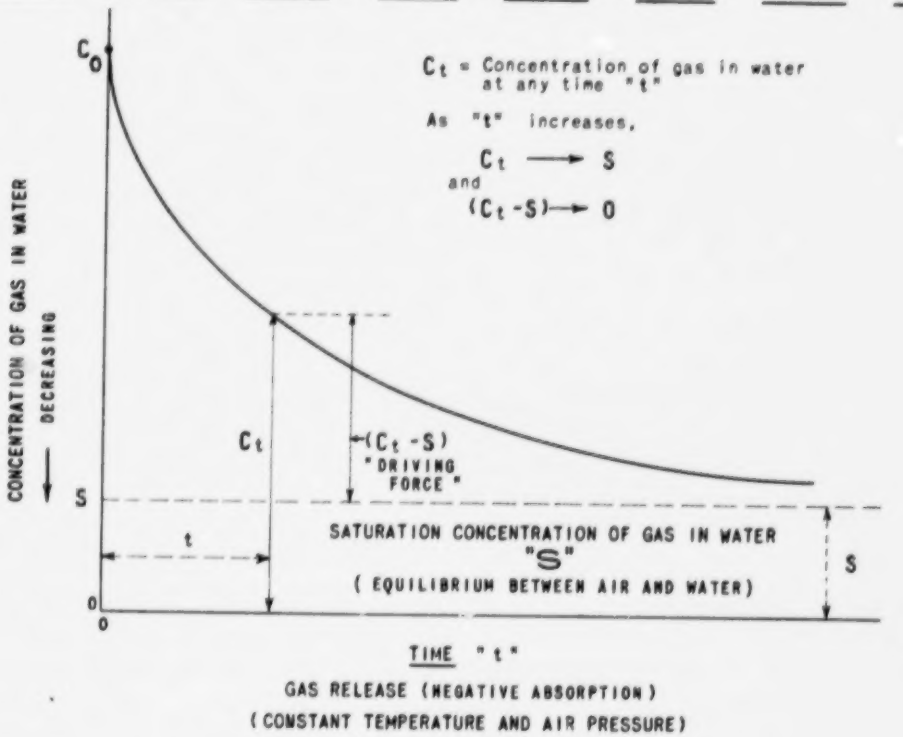
Evidence has already been presented as to the probability of the existence of films at the water-air surface. Applied to aeration of water the theory involves consideration of the resistance to mass transfer offered by these two films at air-water interface. These films are present regardless of the type of aerator used but they may vary in their effect depending on the particular situation. Conditions at the gas-water interface are determined by two factors:

(a) equilibrium between gas and liquid concentrations

(b) all of the gas diffusing through the gas or water film must also diffuse through the water or gas film (9). (Obviously there can be no accumulation of gas at the interface beyond that corresponding to saturation.)

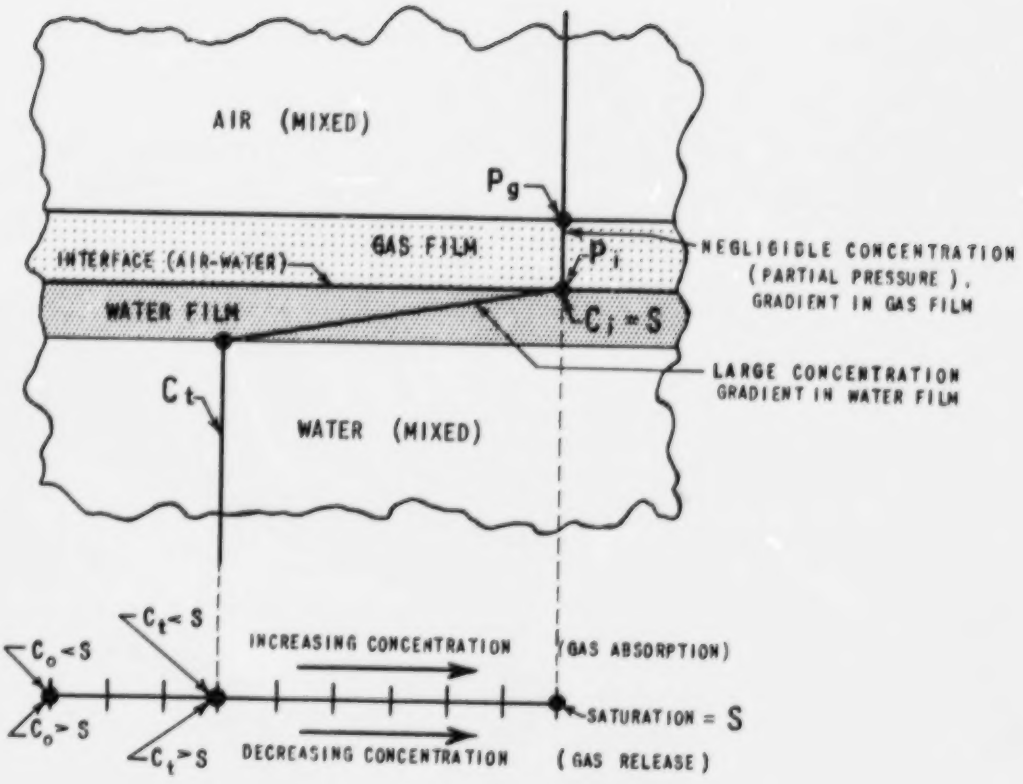
Reference should be made to Figures 2 and 3 in connection with the following sections of this discussion. Figure 2 shows diagrammatically the concentration changes as equilibrium conditions are approached. Figure 3 shows an air-water interface such as would be formed by a water drop, a water layer, or an air bubble in water and the concentration gradients. The drawings do not purport to show the relative film thickness or molecular shape or orientation. They merely offer highly diagrammatic presentations of surface conditions which apparently are of major





GAS ABSORPTION AND RELEASE

FIGURE 2



ARBITRARY DISSOLVED GAS CONCENTRATION SCALE

ABSORPTION OR RELEASE
OF A SLIGHTLY SOLUBLE GAS
(O_2 - CO_2)

FIGURE 3

influence on gas transfer. The resistance encountered by diffusing gas molecules is due to collisions with the molecules of the gas or liquid through which diffusion is occurring. The molecules are much closer together in water than in air. Hence diffusional resistance will be greater in the former. However, resistance is also a function of film thickness and the gas film will probably be somewhat thicker than the liquid film because under comparable conditions of turbulence the film thickness is determined by the kinematic viscosity and this is greater for gases than for liquids (9). In spite of the greater gas film thickness the film of gas offers far less diffusion resistance to slightly soluble gases such as O_2 and CO_2 than does the liquid film. The less soluble gases diffuse so slowly through the liquid film that only a very small concentration difference is required across the gas film. The liquid at the interface will therefore be substantially saturated with the gas solute at the partial pressure (P_g) of the gas. It is unnecessary to consider the gas film further in the calculations for slightly soluble gases such as oxygen or carbon dioxide. (This would not be the case for a highly soluble gas such as ammonia, however.)

Gas Absorption Equation

The gas absorption equation (applicable to the addition of oxygen to water) given by Lewis and Whitman (9) is essentially as follows:

$$\frac{dw}{Adt} = k_L (C_i - C_L) = k_g (P_g - P_i) \qquad \text{(Eq. 5)}$$

(This is a fundamental equation and all others presented are merely variants of it.)

where

w = weight of solute dissolved, grams

t = time, hours

$\frac{dw}{dt}$ = rate of gas absorption, grams/hour

A = area of liquid-gas interface, cm^2

k_g = transfer coefficient through gas film, $gm/(cm^2)(hr)(atmos.)$

k_L = transfer coefficient through liquid film, cm/hr

P = concentration of solute in gas, atmospheres

C = " " " in liquid, grams/c.c.

Subscripts i, g, L apply to conditions at the interface, in the main body of gas, and in the liquid, respectively.

H = solubility coefficient (Henry's Law) in grams/(c.c.)(atmosphere)

(It should be noted that this and other related aeration equations can apply with exactitude only to gas transfer under conditions of constant temperature and pressure and in the absence of appreciable chemical reation.) (9)

At the true interface between liquid and gas substantial equilibrium exists (P_i in equilibrium with C_i).

Therefore

$$C_i = f(P_i)$$

and this function is the solubility relationship given by Henry's Law (Eq. 1)

$$C_i = HP_i$$

For slightly soluble gases there is practically no concentration gradient in the gas film. See Figure 3.

Therefore

$$P_i = P_g$$

and

$$C_i = HP_g$$

For this case (negligible gas film resistance) the following is also valid where K_L represents the overall (both films) gas transfer coefficient.

$$k_L = K_L$$

(k_L values are given in Table 1)

Equation (5) may therefore be written

$$\frac{dw}{Adt} = k_L (C_i - C_L) = K_L (C_i - C_L)$$

or

$$\frac{dw}{dt} = k_L A (C_i - C_L) = K_L A (C_i - C_L)$$

C_i represents the equilibrium concentration in the liquid at the gas partial pressure P_g for any given temperature. As previously noted this is the saturation value of the gas and is subsequently designated as "S" in the equations for gas transfer.

Note the similarity between these equations and the diffusion equation (Fick's Law, Eq. 2).

Equation (5) may be revised somewhat as to nomenclature and also re-written on the basis of rate of concentration change, by dividing both sides of theequation by the volume of water (cubic cm.), as follows:

$$\frac{dw}{Vdt} = k_L \frac{A}{V} (S - C_t)$$

Since $\frac{W}{V}$ represents concentration this equation may be rewritten as

$$\frac{dC_t}{dt} = k^v \left(\frac{A}{V}\right) (S - C_t) \qquad \text{(Eq. 6)}$$

S = saturation concentration of the gas in water in p.p.m.

C_t = concentration of gas in the water at any time "t" in p.p.m.

and

$k^v = (k_L)(10^{-6})$ NOTE: (10^6) $(\frac{W}{V}$ grams/c.c.) = p.p.m.

Any concentration terms may be chosen for S and C_t but "parts per million" is the most convenient term in connection with water aeration.

In the case of gas absorption C_t is less than S. For gas release C_t is greater than S. Assuming gas release is "negative absorption" Equation(6)may be revised to describe the rate of gas release as follows:

$$-\frac{dC_t}{dt} = k^v \left(\frac{A}{V}\right) (C_t - S) \qquad \text{(Eq. 7)}$$

The value $\frac{dC_t}{dt}$ in either absorption or release represents an instantaneous rate and is not applicable to any appreciable time period because as time elapses and gas transfer occurs the value of $(S-C_t)$ or

(C_t - S) changes. The curves in Figure 2 indicate this change for both gas absorption and release.

To determine concentration changes for a given time it is necessary to integrate Equations (6) and (7) between the limits of "0" and "t" for "time" and "C_o" and "C_t" for "concentration" as follows: ("C_o" corresponds to initial concentration; i.e. $C_t = C_o$ when $t = 0$).

Gas Absorption

$$\frac{dC_t}{S - C_t} = k' \left(\frac{A}{V}\right) dt$$

$$-\int_{C_o}^{C_t} \frac{-dC_t}{S - C_t} = k' \left(\frac{A}{V}\right) \int_o^t dt$$

$$\log_e \frac{S - C_t}{S - C_o} = -k' \left(\frac{A}{V}\right) t$$

$$\log_{10} \frac{S - C_t}{S - C_o} = \frac{-k'}{2.303} \left(\frac{A}{V}\right) t = -k \left(\frac{A}{V}\right) t \qquad \text{(Eq. 8)}$$

$$k = \frac{k'}{2.303} = \frac{(k_L)\ (10^{-6})}{2.303}$$

or

$$C_t = S - (S - C_o)\ \ 10^{-k \left(\frac{A}{V}\right) t} \qquad \text{(Eq. 9)}$$

This is essentially the same as the equation developed by Adeney (6) (7) (Equation 4).

Gas Release

For gas release the integrated equation is

$$\log_{10} \frac{(C_t - S)}{(C_o - S)} = -k \left(\frac{A}{V}\right) t \qquad \text{(Eq. 10)}$$

For any situation where $\left(\frac{A}{V}\right)$ is constant Equations (8) and (10) may be reduced to

$$\log_{10} \frac{S - C_t}{S - C_o} = -k_A t \qquad \text{(absorption)} \qquad \text{(Eq. 11)}$$

$$\log_{10} \frac{C_t - S}{C_o - S} = -k_A t \qquad \text{(release)} \qquad \text{(Eq. 12)}$$

where k_A includes the value of $\left(\frac{A}{V}\right)$ and k; $k_A = \frac{(k_L)\ (10^{-6})\ A}{2.303\ V}$

Significance of Equations: The previously presented equations, especially the differential equations (6) and (7) indicate the following:

(a) At any instant, the rate of gas transfer is directly proportional to the difference between the gas saturation concentration (S) and the actual concentration (C_t) in the water. (See Figure 2)

(b) The rate of gas transfer (concentration units) is directly proportional to the area-exposed to volume ratio $\left(\frac{A}{V}\right)$; thus, for a given volume, increasing the area exposed will produce a proportionate increase in rate of gas transfer.

(c) The rate of gas transfer is directly proportional to the gas transfer coefficient k_L (or K_L) which is in turn dependent on the diffusivity of the gas in question and the film resistance.

(d) The total amount of gas transfer is greater as the time of aeration increases. (Eq. 8 and 10)

(e) The percent change in gas saturation deficit ($S - C_t$) or surplus ($C_t - S$) for any given time period is constant based on the deficit or surplus at the beginning of the time period. (Eq. 6 and 7)

(f) Temperature and pressure are important factors because they influence gas solubility (S). Temperature also influences diffusivity and film resistance and hence the value of k_L.

(g) If the performance of an aerator in absorbing or releasing gas is known for one set of conditions, performance under other conditions may be approximated. (Example: An estimate of the effect of doubling the aeration time on CO_2 removal by the installation of duplicate equipment in series with that existing could readily be made provided the performance of the existing installation is known.)

Aeration Equations and Experimental Data

Equations (8) and (10) which describe absorption and release may be rewritten as follows:

Absorption

$$\log_{10} (S - C_t) = -k \left(\frac{A}{V}\right) t + \log_{10} (S - C_o) \qquad \text{(Eq. 13)}$$

Release

$$\log_{10} (C_t - S) = -k \left(\frac{A}{V}\right) t + \log_{10} (C_o - S) \qquad \text{(Eq. 14)}$$

Both of these can be considered to represent the equations of a straight line

$$y = mx + b$$

- provided functions of "y" and "x" are assigned as follows:

$$y = \log_{10} (S - C_t) \text{ (absorption)} \quad \text{or} \quad \log_{10} (C_t - S) \text{ (release)}$$

$$x = t$$

The slope and "y" intercept are defined by the following:

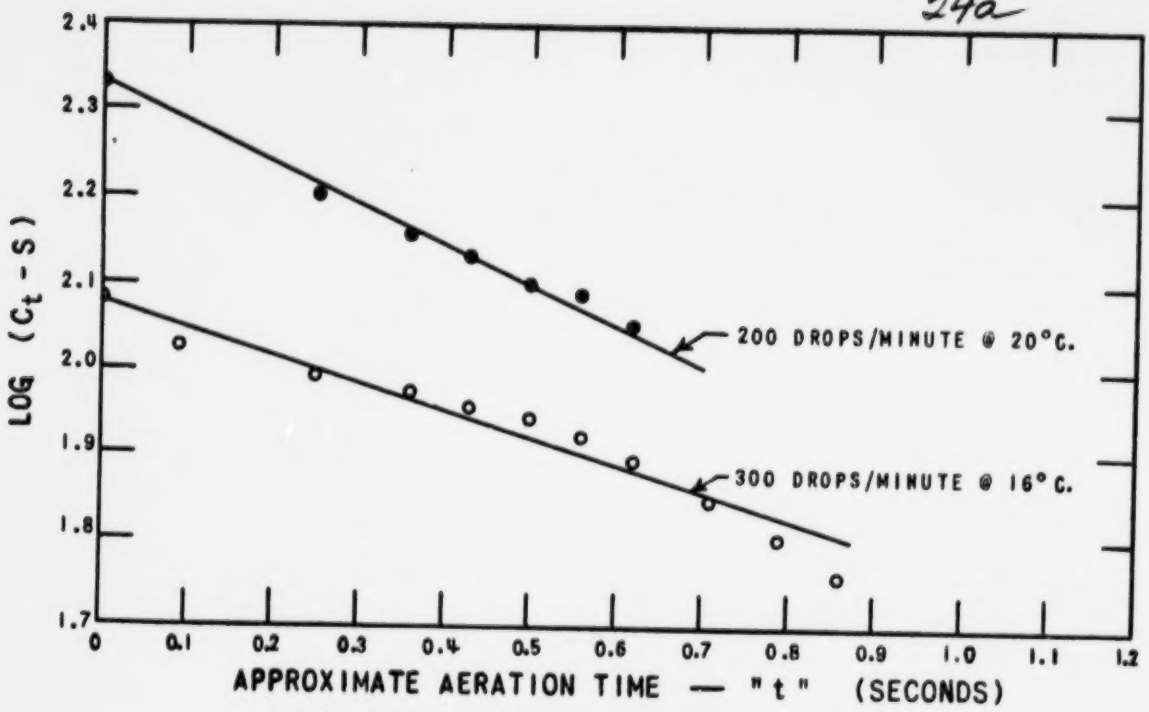
$$m = \text{slope} = -k \left(\frac{A}{V}\right)$$

$$b = \text{y axis intercept} = \log_{10} (S - C_o) \quad \text{or} \quad \log_{10} (C_o - S)$$

If these equations are valid for aerator performance, experimental data appropriately plotted will yield straight lines. The lines shown in Figures (4) and (5) indicate substantial conformance.

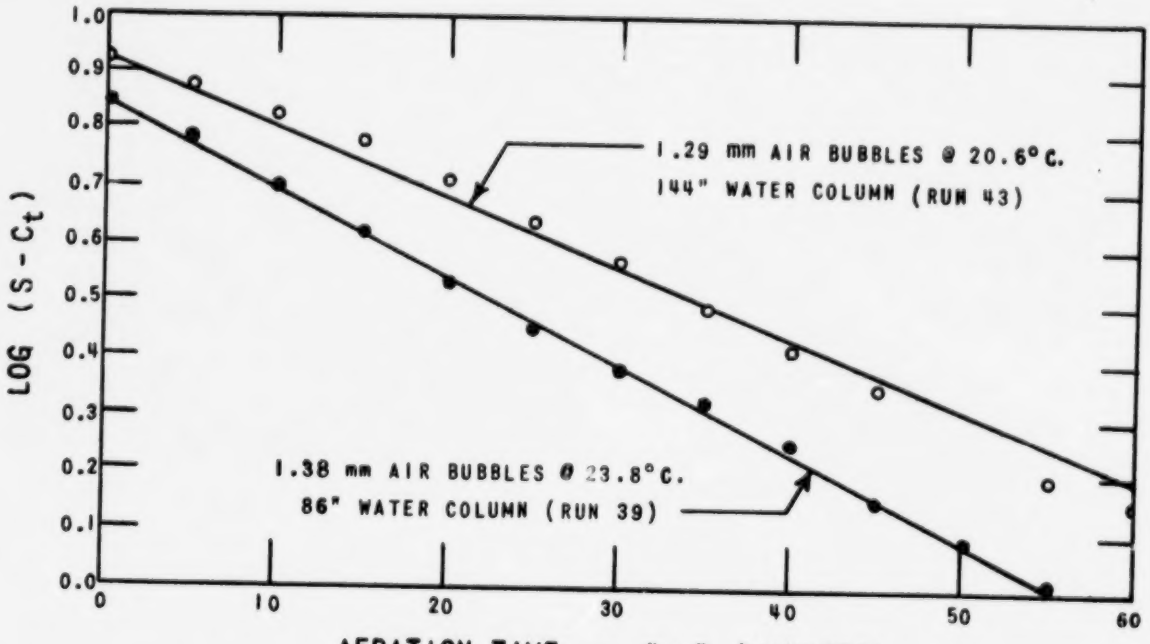
Factors Influencing Rate of Gas Exchange

Temperature: Changes in temperature are important and it is essential that a careful distinction be made between the effect of temperature on equilibrium (gas saturation value, S) and its effect on the gas transfer coefficient k_L, which is a measure of the rate of approach to equilibrium. Increasing the temperature makes the gas less soluble (lower S) thus lowering the rate of absorption (Eq. 8) but increasing the rate of release (Eq. 10). The gas transfer coefficients on the other hand increase with increasing temperature thus making both absorption and release more rapid at higher temperatures for a given saturation deficit or surplus, $(S - C_t)$ or $(C_t - S)$, respectively. The increase in the gas transfer coefficient with temperature is due to decreased resistance plus an increase in the true coefficient of diffusion, D (Fick's Law, Equation 2).



CO_2 REMOVAL — FALLING DROPS
BAYLIS DATA (REFERENCE 10)

FIGURE 4



O_2 ABSORPTION—BUBBLES
IPPEN DATA (REFERENCE 30)

FIGURE 5

Agitation: Agitation of the liquid decreases gas transfer resistance. The effects of agitation on gas absorption coefficients (k_L) have been studied by numerous investigators. Results reported by Hutchinson and Sherwood (33) indicate that the absorption coefficient, k_L, varies approximately as the 0.6 power of the stirring speed above about 100 R.P.M.

Mixing is important for another reason because mixing minimizes concentration gradients within the main body of the water. The film theory will have its most precise application when conditions on both sides of the air-water surface are turbulent (34). This should be and generally is the case in the aeration of water. Bubble aeration produces mixing and there is evidence of circulation of liquid within falling drops due to persistence of motion originating in the spray nozzle (22). Adequate ventilation, natural or artificial, should be provided to insure air turbulence and for other reasons cited in a subsequent section of this discussion.

The highest values of k_L (thinnest films) are apparently encountered just after the formation of a bubble or drop. This phenomenon has been noted by Whitman (36), Baylis (10) and Ippen (30). (See Table 1, water drops.)

Gas absorption coefficients for various conditions are shown in Table 1.

TABLE 1

No.	GAS	TEMP. °C.	CONDITIONS	GAS TRANSFER COEFFICIENT AS k_L cm./hr.	INVESTIGATOR & REFERENCE
			Absorption into Stirred Water		
1	O_2	25	50 c.c. of water; no stirring	0.41	Hutchinson & Sherwood (33)
2	O_2	25	50 c.c. of water; 76 r.p.m.	1.20	"
3	O_2	25	50 c.c. of water; 171 r.p.m.	3.00	"
4	O_2	25	50 c.c. of water; 486 r.p.m.	5.43	"
5	O_2	25	50 c.c. of water; 1025 r.p.m.	7.64	"
6	Air	20	O_2 from air; no stirring	0.4	Becker (33)
			Absorption into Stirred Water		
7	CO_2	25	50 c.c. of water; no stirring	1.46	Hutchinson & Sherwood (33)
8	CO_2	25	50 c.c. of water; 93 r.p.m.	1.65	"
9	CO_2	25	50 c.c. of water; 140 r.p.m.	2.22	"
10	CO_2	25	50 c.c. of water; 171 r.p.m.	2.73	"
11	CO_2	25	50 c.c. of water; 486 r.p.m.	4.84	"
12	CO_2	25	50 c.c. of water; 1025 r.p.m.	8.35	"

No.	GAS	TEMP. °C.	CONDITIONS	GAS TRANSFER COEFFICIENT AS k_L cm./hr.	INVESTIGATOR & REFERENCE
13	O_2	25	10 c.c. bubbles through a water column	20	Schwab (33)
14	O_2	25	Side of a 15 c.c. bubble	31	Adeney (33)
15	O_2	19-22	1.52 to 2.56 mm bubbles thru 25" water column	97	Ippen (30)
16	O_2	20-21	1.51 to 2.13 mm bubbles thru 140" water column	88	Ippen (30)
17	Air	25	O_2 absorption from tip of a 15 c.c. air bubble through a water column	230	Adeney (33)
18	Air	25	O_2 absorption from side of a 15 c.c. air bubble	32	Adeney (33)
19	Air	15	O_2 absorption from 0.24 cm. air bubble through 34 cm. water column	140	Scouller (33) (35)
20	Air	21-25	O_2 absorption from 1.26 to 1.60 mm air bubbles through a 25" water column	205	Ippen (30)
21	Air	20-22	O_2 absorption from 1.29 to 2.05 mm air bubbles through a 140" water column	120	Ippen (30)
			Drops of Water		
22	CO_2	24	0.1 c.c. water drops through gas	260	Whitman (36)
23	CO_2	24	Drops at time of formation	338	Whitman (36)

Film Thickness

Film "thickness" may be considered as an overall measure of resistance to gas transfer. From experimentally obtained values of k_L the apparent thickness of water films under various conditions may be estimated. Based on gas diffusivity data for oxygen and carbon dioxide in water given by Wilke (38) film thicknesses have been computed and are presented in Table 2.

The diffusion coefficients "D" in $cm^2/sec.$ (Eq. 2) as given by Wilke (38) are as follows:

Gas	Temp.°C.	D $(\frac{cm^2}{sec})$	D $(\frac{cm^2}{hr})$
CO_2	18	1.71×10^{-5}	.062
O_2	25	2.6×10^{-5}	.094

Inasmuch as most of the data for k_L are at 25° C. the diffusion coefficient, D_g for CO_2 was corrected to this temperature by the method proposed by Wilke and others (22) (37) (38).

The coefficient of diffusion for CO_2 in water, corrected to 25° C. by this method, is 0.074 $cm^2/hr.$ Film "thickness" or gas transfer resistance is computed from k_L as follows:

$$\text{Film thickness in cm.} = \frac{D}{k_L} = \frac{\frac{cm^2}{hr.}}{\frac{cm.}{hr.}} = \text{cm.}$$

The relative thicknesses or resistance values are more significant than the actual values. Drops apparently have the least resistance but this conclusion is based on limited data. Performance and related data under conditions existing in drop-producing waterfall aerators are not available.

TABLE 2

No. (Table 1)	GAS	TEMP. °C.	CONDITIONS	k_L cm/hr.	D $cm^2/hr.$	APPROX. FILM "THICKNESS" (D/k_L) cm.
			Stirred Water			
1	O_2	25	50 c.c. water; no stirring	0.41	.094	0.23
5	O_2	25	50 c.c. water; 1025 r.p.m.	7.64	.094	0.012
6	Air	20	O_2 from air; no stirring	0.4	.094	0.2
7	CO_2	25	50 c.c. water; no stirring	1.46	.074	0.051
12	CO_2	25	50 c.c. water; 1025 r.p.m.	8.35	.074	0.0089
			Gas Bubbles in Water			
16	O_2	20-21	1.51 to 2.13 mm bubbles thru 140" water column	88	.094	0.0011
21	Air	20-22	O_2 absorption from 1.29 to 2.05 mm air bubbles thru 140" water column	120	.094	0.00078
			Water Drops			
22	CO_2	24	0.1 c.c. drops thru gas	260	.074	0.00028

Gas Partial Pressure

Partial pressure of the gas in the air surrounding the aerator as well as temperature influences the saturation value of the gas in question. Increase in partial pressure of the gas in the air will produce a proportional increase in the value of S. This would be advantageous in the case of absorption (Eq. 8) but a definite disadvantage in the case of gas release (Eq. 10). Ways in which the oxygen partial pressure could be increased significantly would be (a) adding pure oxygen to the air supplied to an enclosed waterfall type or bubble type aerator; (b) by compressing the air as in the bubble type. (Lowering of the partial pressure of oxygen in an enclosed aerator may be prevented by adequate ventilation but oxygen pressure cannot be increased to any great extent by ordinary ventilation.) To date the only practical method for water supply purposes is that of air compression. The use of pure oxygen has been studied in connection with the activated sludge method of sewage treatment (39).

Obviously the saturation value, S, needs to be kept as low as reasonably possible in the case of gas release. Thiscan be accomplished by maintaining as low a partial pressure as possible in the air surrounding the water. Thus for gas release thorough ventilation of structures enclosing aerators is essential. The work of Brown (40) at Memphis, Tenn., confirms this. His conclusion based on pilot and full-scale (30 m.g.d. aerator) observations was that media in a tray type aerator should be so arranged that fresh air continuously passes over the water. It was further concluded that it is impossible to secure consistent

results with an aerator dependent on natural ventilation alone. Fairly uniform results will be obtained if the aerator is not housed and if ventilation is not obstructed by other buildings (40). Ventilation is also of importance from a safety standpoint in the case of removal of CO_2, methane, and hydrogen sulfide. The first named is an asphyxiant (48), the second creates an explosion hazard (13) and the third is highly poisonous (48).

The theory of aeration leads to the prediction that aeration under pressure in a closed tank should be quite efficient as a means of adding oxygen to water but inefficient for CO_2 removal even though the CO_2 removed plus excess air are periodically vented to the atmosphere. Under such aeration conditions the partial pressure for oxygen would be high and its absorption favored. However the partial pressure of CO_2 in the gas pocket in the tank would increase as CO_2 removal occurs thus slowing the rate of release (11).

Practice often requires both O_2 absorption and CO_2 release in the same aerator. This will require diffusion in both directions through the gas and water films and where this requirement is to be met theory indicates adequate ventilation should be provided. This will prevent both lowering of the oxygen partial pressure and increase in the CO_2 partial pressure plus the added advantage of air turbulence.

Forced draft waterfall aerators often employ the counter-current flow principle (11). Air is supplied to the bottom of the aerator enclosure and flows upward counter to the downward flow of the water. From a theoretical standpoint an aerator of this type should be quite

efficient for both oxygen absorption and CO_2 removal. Such an aerator will provide a continuous supply of new air, and thorough gas and water mixing and contact. The application of the counter flow principle would appear to offer an advantage also. CO_2 removal is the most important application of aerators of this type (11) but they should be satisfactory devices for oxygen absorption also.

Considering the case of gas release further, reduction in partial pressure can be obtained by reducing the total air pressure or by the addition of inert gases or both. Vacuum deaerators for boiler feed water utilize the principle of reducing the dissolved air through the combined effects of lowered air pressure plus high temperatures on gas solubility. Installations of large, cold-water, deaerating systems based solely on pressure reduction have been described by Powell (12) and Speller (41). Ippen (30) mentioned the use of nitrogen "stripping". Nitrogen was bubbled through partially deaerated water as a means of reducing dissolved oxygen to low levels in connection with aeration experiments.

Theory of Hydrogen Sulfide Removal: Hydrogen sulfide removal presents a special aeration problem which is of considerable theoretical and practical interest. Hydrogen sulfide is a fairly soluble gas and is objectionable in water supplies because of its unpleasant odor at very low concentrations, corrosiveness, and high chlorine demand (11) (43). It can be removed by aeration but its removal is complicated by several factors. H_2S removal has been studied by Nordell (11), Derby (42), and Powell and von Lossburg (15). One of the most important properties of hydrogen sulfide (H_2S) is its solubility in relation to that of CO_2. Unfortunately

it is about three times as soluble as CO_2 (11). Therefore when water is aerated the CO_2 comes out much more rapidly than the H_2S thus raising the pH of the water and shifting the H_2S ionization equilibrium toward the formation of more sulfide (HS^- and S^{--}) which cannot be removed by aeration. Another complication is the fact that aeration introduces oxygen which reacts with the H_2S forming water and free sulfur. The latter reaction reduces the sulfide content but unless the sulfur formed by this reaction is removed it may create further serious problems in connection with chlorination and water distribution (42) (43). Problems associated with sulfur bacteria following aeration have been described by Derby (42).

The efficiency of H_2S removal by aeration, i.e., actual transfer of H_2S from the water to the air, can be increased by aeration of the water in an atmosphere containing a high partial pressure of carbon dioxide. Such an atmosphere can be furnished by waste flue gases or by recarbonation equipment and will contain of the order of 10% CO_2 as compared to about .03% in ordinary air. This is a very large concentration or partial pressure increase. The result is that the CO_2 content of the water increases during aeration thus lowering the pH and maintaining it at a low value. The latter condition favors the H_2S form of the sulfide content of the water and transfer of H_2S is effected. The CO_2 added can be removed in a second aerator of conventional design. The basic principles involved are those of good aeration practice plus provision for lowering the pH and maintaining it at a low value during the aeration process. Every H_2S removal problem has its own peculiarities and while the principles cited are valid, each case should be given experimental study prior to the installation of full scale equipment (15).

Removal of Tastes and Odors

No adequate theory can be proposed to describe the physical removal by aeration of the majority of taste and odor producing compounds. This stems from the fact that there is very little knowledge as to the physical and chemical nature of the vast majority of these compounds. From the theory that has been developed certain basic principles may be cited. However, for any specific situation trial is the only method of determining what results can be achieved in the way of threshold odor reduction by aeration.

From the previous discussion of the theory of gas transfer it is evident that solubility is an important characteristic of compounds which are to be removed or reduced by aeration. Another important characteristic is the vapor pressure of the substance. This may be defined as the pressure at which the liquid and its vapor are at equilibrium at a given temperature (10). The vapor pressure of all substances increases with increasing temperature and the temperature corresponding to a vapor pressure of one atmosphere is the true boiling point of the substance. Up to this point vapor pressure has not been stressed because the gases thus far considered all have very high vapor pressures at extremely low temperatures. The boiling point for O_2 is -183° C. and for CO_2 - 78° C. (37).

Some idea of relative vapor pressure of a substance may be obtained from its boiling point. High boiling point substances have lower vapor pressures at a given temperature than those with low boiling points. Substances such as phenol which have a fairly high boiling point have an almost negligible vapor pressure at ordinary temperature. The vapor

pressure of phenol is so small that it would not be at all practical to attempt its removal by aeration. Water temperatures usually vary from about 0° C. to 25 or 30° C. at the most. Within this temperature range compounds which boil at much more than about 0° C. probably cannot be removed by aeration unless their solubility is quite low (11). Chlorine with a boiling point of about -34° C. cannot be removed readily because of its fairly high solubility and tendency toward compound formation with water or substances in it.

For any particular compound if the two factors: solubility and boiling point (an indication of relative vapor pressure) are known a rough estimate as to the probable efficiency of aeration on its removal can be made. In general such estimates will show that nearly all known taste and odor producing compounds (except H_2S) cannot be effectively removed by ordinary aeration processes. (This discussion does not pertain to possible subsequent oxidation of these compounds by dissolved oxygen added by aeration. Certain taste and odor producing compounds may be changed chemically during passage through subsequent treatment units by the dissolved oxygen added by aeration. This is known to occur in the case of H_2S.)

Theoretical Aspects of Aeration Practice

Time vs. Surface: In discussing aeration performance Langelier (44) has called attention to the reciprocal relationship between water-air surface exposed and time. This relationship will be evident from an inspection of either Equation (8) or (10). For a given situation as long as the product of $(\frac{A}{V})$ (t) remains constant the performance will be the same.

Therefore, if other things remain the same "t" may be increased at the expense of "$\frac{A}{V}$" without loss of efficiency and vice versa. The following example by Langelier (44) indicates this relationship. The effective exposure, $\frac{At}{V}$, of water stored in an open basin 10 ft. deep for 0.5 hour will be equivalent to the effective exposure, $\frac{At}{V}$, of 1 cm. drops falling a distance of 15 ft. However as pointed out by Langelier (44) in making this comparison allowance must be made for the greater turbulence (and hence thinner films and lack of concentration gradients) in the falling drops. This latter factor is in favor of the falling drops. Nevertheless it must be concluded that in the passage of water through a typical water plant considerable gas exhange will probably be obtained (44).

Use is made of the reciprocal relationship between time and area exposed in various types of aerators. In the waterfall type maximum surface can be obtained by drop-producing spray nozzles but time of exposure will be short unless there is considerable expenditure of head to force the water high into the air. On the other hand, tray and cascade aerators generally produce less surface area but the time of exposure may be greater because more time is required for water to fall through a series of trays or over cascades with alternate starting and stopping than to fall freely through the same vertical distance. As an example, (based on falling body formulae - air friction neglected) for an aerator containing N equally spaced trays, the ratio of the aeration time provided by this type to that provided by a jet of water rising and falling the same distance is $\frac{\sqrt{N}}{2}$. Thus for a four tray aerator the theoretical aeration time would be the same as for a jet but would be

greater for any larger number of trays. As in the other examples, other factors than time come into play so a comparison cannot be made strictly on the basis of time.

One factor which probably is of some importance in favor of a tray or cascade aerator is the apparent rapid rate of gas transfer in newly formed drops and water layers. Conditions are favorable for repeated destruction of old and formation of new surfaces in a tray or cascade aerator.

Time Factor - Waterfall and Injection Aerators: Installation statistics (45) show that practice favors the waterfall type of aerator in the water works field. This type has many practical as well as certain theoretical advantages. In theory the waterfall type, particularly that employing sprays or jets, will break the water into turbulent thin layers and drops, which will have a high gas transfer coefficient (thin films) and a large surface to volume ratio. Certain theoretical as well as practical disadvantages of the waterfall type have been recognized. The principal theoretical disadvantage is the relatively short time of exposure that can be provided. The water in a jet rising 10 feet and then falling travels at an average rate of about 13 feet per second (falling body formulae) and thus has only about a 2 second exposure to the air. On the other hand a bubble of air of the size often employed with injection aerators has very little acceleration and a terminal velocity of the order of 1 foot per second (30) (46). Thus a bubble rising through a water depth of 10 feet has a time of contact of around 10 seconds or about 5 times the time available to the rising and falling drop. For an

approximately equal expenditure of energy a substantially longer contact period can be obtained. Langelier (44) used the following example to illustrate this point. Assume one volume of water aerated with an equal volume of air (measured under a pressure = water depth H) subdivided into bubbles of radius (r) in a basin of depth H. Assume a second equal volume of water subdivided into drops of the same radius (r) and allowed to drop through the same height H. The energy requirements of the two methods are about the same. The effective exposure for the drops ($\frac{At}{V}$ factor) = $\frac{3}{r}\sqrt{\frac{2H}{g}}$ while the same factor for the bubbles is $\frac{3H}{\mu r}$ for a bubble rising velocity of "μ" ft./sec. The ratio of the effective exposure factor for the bubbles to that of the drops is $\frac{1}{\mu}\sqrt{\frac{gH}{2}}$ where g is the acceleration due to gravity = 32.2 ft./sec./sec. If μ = 1 ft./sec. then the ratio is $\sqrt{\frac{gH}{2}}$. Based on the assumptions made, for an air injection basin 16 feet deep the product of interface and time ($\frac{At}{V}$) is about 16 times greater than for a waterfall aerator providing 16 feet of free fall. This suggests a theoretical advantage in favor of the air injection aerator despite greater resistance to gas transfer resulting from thicker films. On the other hand the time of exposure for the drops could be doubled without additional energy expenditure by the use of a nozzle which would jet the water 16 feet into the air initially. The $\frac{At}{V}$ factor for the drops would then become $\frac{6}{r}\sqrt{\frac{2H}{g}}$ and the ratio $\frac{1}{2\mu}\sqrt{\frac{gH}{2}}$ or $\sqrt{\frac{gH}{8}}$ for μ of 1 ft./sec. Thus for a situation such as this and a basin 16' deep the $\frac{At}{V}$ ratio for the bubble is only about 8 times that for the drops.

A factor of some importance in the efficiency of bubble aerators is the pattern of flow of the water in the aeration basin as induced by the bubbles themselves. A spiral flow pattern is desirable for two reasons; (a) high water surface velocities are created which promote gas transfer; (b) a substantial number of bubbles do not escape to the atmosphere immediately but are carried across the aeration basin and held in a more or less fixed position by the descending water. In this position the buoyancy of the bubble is just balanced by the drag of the descending water. For these reasons spiral flow aerators are more efficient than the older ridge and furrow style.

Formation of Air Bubbles: The efficiency of injection aerators depends to a great extent on the size of the bubbles of air formed by the air injection equipment. The size used will be a compromise between the increased efficiency associated with small bubbles and the practical problems of maintaining equipment to produce them. In this connection certain theoretical considerations and experimental data are of interest.

For orifice air injectors the production of bubbles is related to both orifice diameter and rate of gas flow (30). Single bubbles are produced under conditions of low gas flow rates and their diameters are a function of the diameter of the orifice alone.

The size of a single bubble formed at low air flow rates by a simple injection device such as a submerged pipe containing multiple air outlet orifices is the resultant of a balance between two forces: (a) the buoyant force of the bubble which tends to separate it from the orifice, and

(b) the shear force necessary to break the surface tension across the orifice. The bubble must grow to a certain size in relation to the orifice before it can break away. Maier (46) found the relationship between static bubble radius and orifice radius to be about 10:1 for water and solutions of similar surface tension. Using a capillary tube orifice with a bore diameter of .1148 mm, Ippen (30) reported that up to a critical gas flow rate of about 72 c.c./minute the bubbles emerged in single formation with a constant diameter of 1.28 mm or about 11 times the orifice diameter. Above this critical gas flow rate the bubble diameter increased with increasing gas flow and the bubbles emerged in chain formation. From this and other information (47) it appears that very small bubbles cannot be produced without the use of orifices of extremely small diameter - so small in fact that they probably would not be practical because of rapid clogging. Work conducted by Beck (47) on porous diffuser plates confirmed the observation that the advantage gained by producing small bubbles through the use of devices of low permeability probably is not worth the extra burden of maintenance which such devices impose.

The fact that the diameter of bubbles formed will be of the order of at least ten times the orifice diameter suggests a minimum spacing of at least 10 orifice diameters between orifices in order to minimize the chance for coalescence of the bubbles after they are formed (46).

Much of the work conducted by Maier (46) on bubble formation was aimed at the production of small bubbles using fairly large air injection orifices. He reported successful results on a laboratory scale using various devices to produce a shearing stress on the bubble sufficient to

cause it to break away from the orifice while still of small size. Langelier (44) also carried out work on devices employing this principle. This method properly applied would have the obvious advantage of producing small bubbles while releasing air through fairly large orifices not subject to the clogging problems associated with small orifices.

Rising Velocity of Bubbles: Information presented by Ippen (30) indicates that the terminal velocity (balance between lift and drag) reaches a maximum at a single bubble size of 0.6 mm diameter (0.02 inch). This maximum velocity is about 32 cm./sec. (1.05 ft./sec.). For slightly larger bubbles the velocity of rise decreases slightly with further increase in bubble size reaching a minimum value of about 25 cm./sec. (0.8 ft./sec.) at a bubble diameter of about 3 mm. (0.1 inch). Further increase in diameter results in greater velocity, a bubble of 10 mm diameter (0.4 inch) having a rising velocity about equal to a 0.6 mm bubble; i.e. about 1 ft./sec.

Porous air diffuser plates of the permeability most commonly used produce bubbles of 0.1 to 0.12 inch diameter (21).

Drop and Bubble Surface Areas: The factor $(\frac{A}{V})$ representing surface contact area available for gas transfer per unit of volume is of importance in aeration efficiency. Rate of gas transfer is directly proportional to this factor (Equations 8 and 10). Consideration of the relationship between the surface area and the volume of a sphere is therefore of some interest in any theoretical discussion of aeration. Air bubbles rising through water and drops falling through air may be assumed to be nearly spherical in shape so the principles discussed here apply

to some extent to both types of aeration devices.

Area of sphere = A = πd^2 where d = diameter

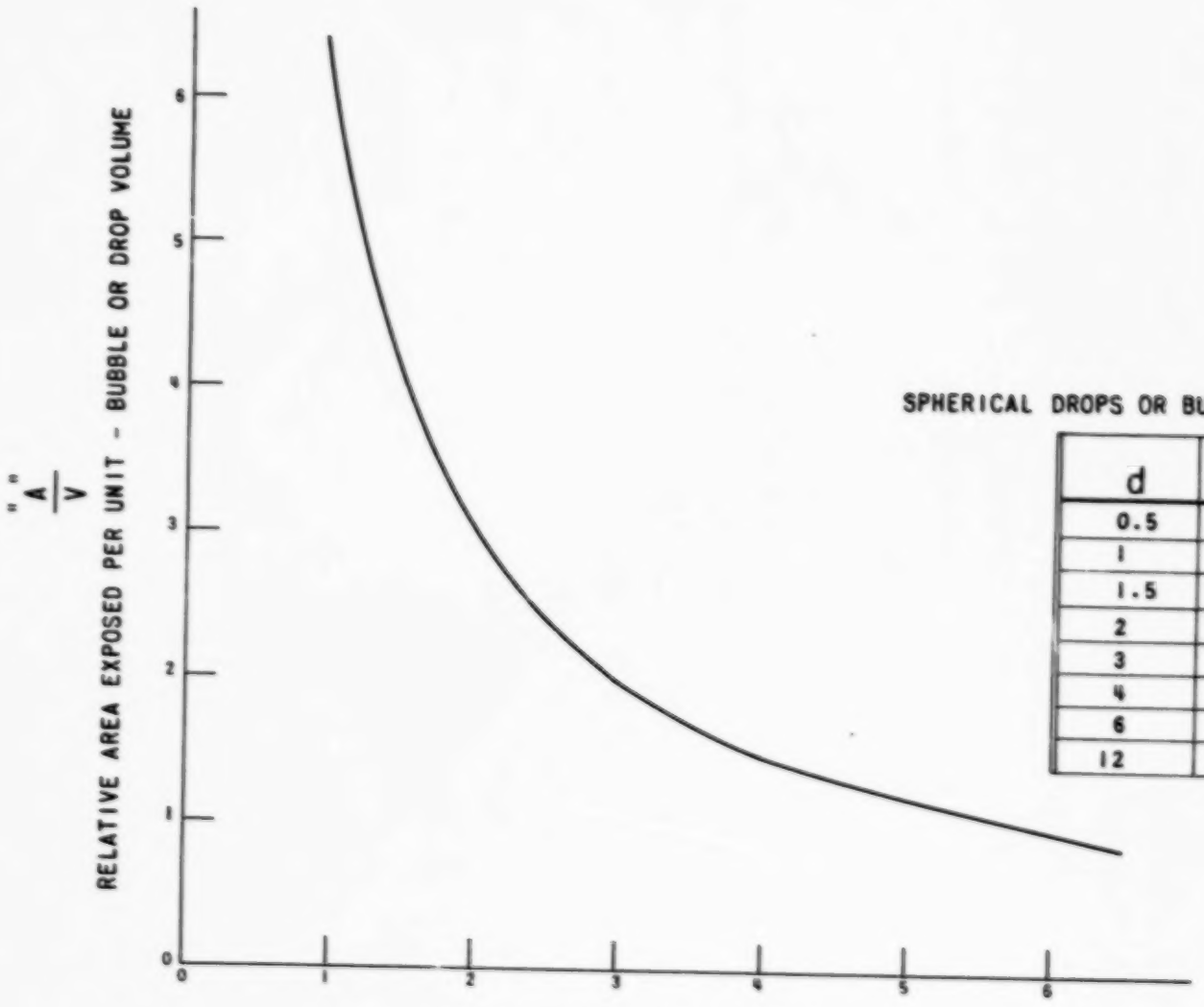
Volume of a sphere = V = $\frac{\pi d^3}{6}$

$$\frac{A}{V} = \frac{\pi d^2}{\frac{\pi d^3}{6}} = \frac{6}{d}$$

Figure 6 indicates this relationship graphically. Note that when "d" is small $\frac{A}{V}$ is large and when "d" is large $\frac{A}{V}$ becomes small. Inasmuch as for any fixed conditions of concentration difference, $(C_t - S)$ or $(S - C_t)$, and gas transfer coefficient k, rate of gas transfer is proportional to $\frac{A}{V}$, the efficiency of aeration will decline with increasing drop or bubble diameter in about the same way as the $\frac{A}{V}$ factor shown in Figure 6 declines.

Some idea of the enormous area involved when small bubbles or drops are produced may be obtained from considering 100 cubic feet of air or water. One hundred cubic feet of either in the form of a single sphere would have a surface area of about 104 sq. ft. However divided into drops or bubbles 0.1 inch in diameter the surface area becomes about 72,000 sq. ft. or over 1.5 acres and the $\frac{A}{V}$ factor has changed from 1.04 to 720/ft. ($\frac{A}{V}$ has the dimensions of $\frac{1}{\text{length}}$; that is $\frac{1}{\text{ft.}}$ in this case).

Theoretical considerations (46) serve to emphasize the importance of obtaining as much uniformity with respect to bubble or drop size as



SPHERICAL DROPS OR BUBBLES - $\frac{A}{V} = \frac{6}{d}$

d	$\frac{A}{V} = \frac{6}{d}$
0.5	12
1	6
1.5	4
2	3
3	2
4	1.5
6	1
12	.5

AREA - VOLUME AND DIAMETER RELATIONSHIP

FIGURE 6

possible. The volume of a spherical drop or bubble increases as the cube of the diameter and even a small percentage of large bubbles or drops can reduce the surface area exposed and hence aeration efficiency considerably as indicated in the following example.

In the previous case involving the 100 cubic feet of air or water, assume 99% of the bubbles or drops are 0.1 inch in diameter but that the other 1% have a diameter of 0.5 inch. Dividing the 100 cubic feet of water or air in this way will produce about 147 million bubbles or drops of which 1.47 million will have a diameter of 0.5 inch and a volume of about 56 cubic feet. The other 99% which have a diameter of 0.1 inch will have a volume of only 44 cubic feet. In other words 1% of the bubbles or drops will contain 56% of the total volume. For the 0.5 inch bubbles or drops the surface area will be about 800 square feet. For the 0.1 inch bubbles or drops the surface area will be about 32,000 square feet. The total surface area and $\frac{A}{V}$ factor will therefore be about 33,000 square feet and 330 per foot, respectively, or less than half that available when all bubbles were 0.1 inch in diameter. Viewed another way with only 1% of the bubbles or drops being 5 times oversize, rate of gas transfer will be decreased by over 50%.

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